Table 3
CHIPPS ISLAND TAG SUMMARY AND SURVIVAL CALCULATIONS AND EXPANDED FISH FACILITY RECOVERIES FOR CODED-WIRE-TAGGED SMOLTS RELEASED IN 1995

Tag Code	Release Site	Release Date	Truck Temp.	Release Temp.	Number Recovered	Survival Index	Group Survival Index	SWP Expanded Salvage	CVP Expanded Salvage
6-1-14-5-1	Mossdale				11	0.21		12	1245
6-1-14-4-14	Mossdale				12	0.23		24	1487
	Total	17-Apr-95	50.5	57	23		0.22		
6-1-14-4-12	Dos Reis	17-Apr-95	51	57	8		0.15	0	1
6-1-14-4-13	Jersey Point	19-Apr-95	51	60	25		0.46	0	0
6-31-47	Dos Reis	05-May-95	50	63	21		0.39	0	0
6-31-50	Mossdale				10	0.19		20	1019
6-31-51	Mossdale				3	0.06		54	840
	Total	05-May-95	49	62	13		0.12		
6-31-49	Dos Reis	17-May-95	56	65	9		0.16	0	24
6-1-14-5-4	Mossdale				1	0.02		66	720
6-31-48	Mossdale				7	0.13		62	732
	Total	17-May-95	49.5	63	8		0.07		
6-1-11-4-1	Upper Merced				5	0.17		102*	313
6-1-11-4-2	Upper Merced				3	0.10		148	255
6-1-11-4-3	Upper Merced				4	0.14		229	423
6-1-11-4-4	Upper Merced				6	0.20		139	351
	Total	03-May-95	51	51	18		0.15		
6-1-11-4-5	Lower Merced				7	0.24		137	341
6-1-11-4-6	Lower Merced				4	0.13		123	475
6-1-11-4-7	Lower Merced				7	0.23		154	418
	Total	04-May-95	51	59	18		0.20		
6-1-11-3-11	Upper Tuolumne				8	0.26		474	510
6-1-11-3-12	Upper Tuolumne				5	0.18		177	461
6-1-11-3-13	Upper Tuolumne				8	0.26		277	572
	Total	04-May-95	51	48	21		0.25		
6-1-11-3-14	Lower Tuolumne				5	0.18		236	607
6-1-11-3-15	Lower Tuolumne				7	0.25		203	707
	Total	05-May-95	48	51	12		0.22		

* This SWP expanded value is preliminary.

Survival indices for Mossdale and Dos Reis releases with Feather River stock (Table 3) were higher in 1995 than for similar releases in 1996. Similarly, smolts released in the tributaries (Merced River stock) survived at higher levels in 1995 than in 1996. The similar indices for all four tributary groups within a year indicates that mortality of the marked fish in the delta is overpowering mortality in the tributaries.

Survival in 1995 between Mossdale and Chipps Island was higher (by about 9 times) than in 1996. The difference could be partly associated with the somewhat different ratios (5:1 versus 4:1) but more likely reflects the higher flow or the greater difference between flow and export in 1995. The barrier was not in place for either group. Comparison of groups released at Dos Reis with those released at Mossdale in 1995 and 1996 indicated a 30-70% increase associated with the barrier, assuming that the Dos Reis release group survival would represent survival of a Mossdale group released with a barrier in place.

Further studies in 1997 will address the relative importance of flow and export to smolt survival in the southern delta. An draft proposal is under review.

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Science, Policy, and the Interagency Program

Wim Kimmerer and Bill Bennett

Misunderstandings have arisen in discussions of bay/delta environmental issues about what constitutes science, how ecosystems (and ecology) function, and in particular, how to deal with uncertainty in scientific findings. This essay describes our views of the nature of science, particularly ecological science, and how it can support effective management and policy-making. We then evaluate the ability of the Interagency Ecological Program to provide valid scientific input to policy-makers, drawing on our experiences as members of the Estuarine Ecology Team. We conclude that Interagency Program is doing a creditable job of providing scientific input for policy decisions, although there will always be room for improvement.

The Nature of Science

Science is often portrayed as a deliberative gathering of facts. Missing from this picture are the creative, anarchic, and consensual aspects of science. Science is creative in the development of new ideas, theories, or methods; anarchic in the way that the entire process lurches toward understanding; and ultimately consensual in the way that new ideas are either accepted or rejected. Science is imperfect and scientists are often wrong; we discuss this further below.

Science is not simply the accumulation of facts, but a way of knowing about the natural world (Gould 1979; Futuyma 1983). In the scientific process facts (*ie*, data) are gathered through observation and experiment. Creativity enters science in the way that new ideas are incorporated into the existing body of knowledge and in the development of new theories.

Darwin pointed out that facts are not very interesting unless they contribute to the development or testing of a theory. A scientific theory is a system of ideas that accounts for or explains a group of observations in a complete and self-consistent way. It may be revised, or even replaced, as new information becomes available. This differs vastly from the general definition of "theory", which includes such ideas as "conjecture", "speculation", and "unproved assumption". A scientific theory is an idealized description of a part of the real world. It is the best description the scientists can devise that is consistent with current information.

A theory is only the first step in the scientific process. Theories arise out of the attempts of scientists to explain observations. For a theory to be useful, it must not only explain previous observations but also predict observations not yet made. To accomplish this, the theory, or parts of it, must be framed as hypotheses, which are statements arising from the theory that lend themselves to testing. For example, from Einstein's general theory of relativity arises the prediction that light is bent by strong gravitational fields, from which could be developed a hypothesis about gravitational lenses. Many theories, including Einstein's, have been subjected to numerous tests through this cycle of prediction, hypothesis, and testing through controlled observations. Some have weathered these tests without the need for modification; indeed, as far as we are aware, all of the predictions of Einstein's theory have been borne out (except of course the one about dice).

Sometimes theories collapse under the weight of newly discovered observations. For example, data inconsistent with immovable continents stimulated development of the plate tectonic theory, which completely revolutionized geology and provided an internally consistent framework to explain the new observations. More commonly, though, theories are modified to accommodate new observations. Darwin's theory of evolution has passed the test of time in general terms, but many of the specific features of that theory (*eg*, the idea that evolution is necessarily gradual) have been modified as new observations have been made.

The anarchic aspect of science arises because any scientist is free in principle to test the theories of other scientists. Indeed, there is tremendous incentive for young scientists in particular to make a name for themselves by refuting or modifying some widely-held theory. This means that flawed theories sooner or later show their weaknesses to the probing community of scientists, and theories that provide an accurate and useful depiction of the natural world are more likely to survive than those that do not.

The chaotic tendency in science is roughly balanced by a process of consensus. This process operates in an informal way to resolve disputes arising from conflicting theories and differing sets of observations. The consensus process operates through two complementary pathways: publication of results in peer-reviewed journals, and a general insistence that results obtained in one location be replicated by other scientists in other locations. Peer-review is an imperfect process, and some papers are published that in retrospect ought not to have survived. When other scientists recognize major flaws in a paper or fail to replicate the results reported, interest in these results wanes. Thus the process of consensus has a self-cleansing effect on the progress of science. The main drawback to consensus is an inherent conservatism and resistance to non-conforming ideas.

To summarize, the scientific method comprises gathering of information, development of theories, testing of hypotheses, and dissemination and validation of results. Without all these steps, investigations fall short of what we would call "science".

Ecological Science

None of the examples of theories given above are ecological theories, and with good reason: the complexity of ecosystems and the relative youth of the science makes non-trivial, general ecological theories hard to find and even harder to test. The complexity of ecological systems has required novel methods for evaluating theories and testing hypotheses. Reductionist approaches, effective in other scientific disciplines, have proved ineffectual for ecological questions. Reductionist approaches prescribe that complex systems be examined in their parts, and that theories be deduced by sequentially rejecting all alternative hypotheses through explicit experimentation. The interconnectedness of ecosystems, however, almost guarantees that no single causative pathway can be identified for an observed effect, thereby dooming the purely reductionist approach to failure.

Ecologists have been hybridizing aspects of reductionism (Schoener 1986), holism, and dialectical philosophies (Levins and Lewontin 1985) into an increasingly coherent investigative strategy (Diamond and Case 1986). Ecological hypothesis-testing, particularly for environmental problems, often employs interdisciplinary teams that carefully consider and examine the relevant spatial, temporal, and biological scales (Diamond and Case 1986), and the degree to which individual factors interact to produce ecological patterns (Bennett and Moyle 1996; Polis and Strong 1996).

Reductionist approaches to ecological questions have often mismatched or ignored the consequences of scaling (Bennett 1990) or exaggerated the importance of single factors relative to other factors. Furthermore, most ecological systems are continually changing, so causative links are a moving target. Moreover, the dynamics of many systems and populations may be chaotic over the time and space scales of interest to society. Thus, the intractable nature of ecological systems limits the level of certainty in ecology (Ludwig *et al* 1993).

Several consequences flow from the difficulties discussed above. First, although the fundamentals of ecology appear rather simple, the actual practice can be maddeningly difficult; ecosystems do not reveal their secrets readily. Second, an observed pattern may not have a single identifiable cause. Third, because systems vary among locations, theory applicable to one location may not be applicable to another. Fourth, there is more uncertainty, and therefore more scope for disagreement, about issues that the public deems important.

Ecology and Management

An inherent mismatch exists between the needs of managers and policy-makers for information to support decisions and the ability or willingness of scientists to stick their necks out to provide that information. Ideally, an interaction between scientists and managers would address problems requiring scientific input in a timely manner and would subject results to a rigorous, peer-reviewed investigation. Rarely does this happen; more often, decisions must be made quickly and scientists are asked to provide answers based on expert opinion or on investigations designed for other purposes. There is no way around this, given the short time scale for decision-making and the relatively long turnover time for any thorough scientific investigation.

Another difficulty with the application of science to policy is that the most knowledgeable and productive scientists in a given field are unlikely to be the same ones providing scientific advice on a daily basis. Usually this advice comes from agency scientists or consultants who, though they may be no less capable than the best researchers in the field, are often on career paths that limit the pursuit of their research interests. Many of the activities of scientists working or consulting for resource agencies have a scientific tone but do not apply the scientific method. For example, monitoring for the purpose of establishing compliance with regulations uses scientific techniques but is not designed to test hypotheses related to theories. Likewise, prediction of environmental impacts of a proposed project requires extensive ecological understanding, but since the predictions are rarely framed as experiments this does not qualify as science.

What can be done to improve the way science is used to support policy? Below we suggest some fundamental approaches that should promote the best scientific inputs and state our opinions about Interagency Program activities in each area.

Encourage Peer Review and Publication

The only legitimate validation of a scientist's work is in the public arena of peer review. Publication in peer-reviewed journals has several advantages to justify the time commitment. First, preparing a manuscript for publication forces the scientist to think through methods, results, and conclusions in a more critical way than when writing to a narrower audience. Second, publication holds the scientist's work up for scrutiny beyond his or her own organization, resulting usually in an improvement of that work and ultimately in its validation as "good" science. Third, publication and presentation of findings introduces the scientist to peers whose advice and suggestions, usually obtained at no cost, can be highly valuable in improving the quality of the science.

Efforts within the Interagency Program to publish results vary among agencies. An unavoidable conflict arises between the interest of the Interagency Program in publication, and the shorter-term needs of member agencies for staff time. Therefore, many of the findings of the Interagency Program that have become common knowledge within the program have either not been published or have been published only with the assistance of scientists from outside the Interagency Program (*eg*, Jassby *et al* 1995). The Science Advisory Group has recommended more emphasis on publication, and Interagency Program management appears to be responding positively.

Seek Outside Collaboration and Review

Science does not benefit by isolation. In addition to peer review of final products, scientists and agencies should actively pursue collaboration, advice, and review by scientists from other organizations, particularly universities. The distinction between academic and applied science has become blurred, and this trend should be encouraged. Outside collaborators can provide expertise in areas not represented within an agency. Perhaps more important, the experience of such collaboration is beneficial to the agency scientists from the standpoints of education and enthusiasm about their work. Science is not a static process, and the most effective scientists are always learning from others.

The Interagency Program has a number of collaborators from outside the agencies, including ourselves, several other academic and consulting scientists, and the Science Advisory Group. In addition, there has been a long and healthy history of seeking outside advice.

Conduct Experiments

"Adaptive management" (Holling 1978) is an effective way to manage complex systems. This method entails investigations into the consequences of actions taken and requires continual adjustment to new conditions and new knowledge. These can be framed as experiments, although in cases involving alteration of the entire system, the lack of controls makes experimentation difficult.

The Interagency Program has demonstrated considerable flexibility lately in responding to changes in the ecosystem and in policy. However, only a few times has the system been manipulated for experimental purposes; perhaps the best example is from the entrapment zone investigations in the 1970s (Arthur and Ball 1979).

Conduct Investigations Into Fundamental Questions

There is a natural, and justifiable, tendency for organizations such as the Interagency Ecological Program to focus attention on answering immediate and practical questions; *eg*, what is the abundance of a species of fish, how is it changing, or how does a particular operation such as pumping affect it. Questions of a more fundamental nature are often not perceived as immediately relevant enough to be supported. Nevertheless, the answers to these questions may be extremely useful in interpreting the patterns of change in space and time and the consequences of management activities. For example, the observation that freshwater flow and abundance of young striped bass are related should prompt an investigation into the cause. If the cause is reduced exposure to entrainment under high flows, actions to reduce entrainment (such as moving the export facility) might benefit this species. If, on the other hand, the cause is changes in habitat, moving the facility might have no effect.

Obviously, managers should be interested in the outcome of such an investigation. There is a tremendous range of potential research topics without obvious immediate payoff but that would enhance the interpretation and understanding of ecosystem dynamics and causative relationships. These are fundamental questions in ecology that could be answered in a way to help managers. Examples include: What limits the population of a particular species? To what extent are the system and its components resource limited? How do feedbacks among system components result in controls or limitations? What are the sources and rates of mortality in a population?

Some member agencies of the Interagency Program have been reluctant to facilitate basic research. Nevertheless, the Interagency Program as an organization continues to support research that addresses fundamental questions with potential management implications. The demise of the Research Enhancement Program was an unfortunate setback in furthering this aim, although we believe that program could have been integrated better with ongoing Interagency Program investigations.

Recognize Inherent Uncertainties and Limitations

An ecosystem is an extraordinarily complex thing, and complete understanding will never be achieved. The answer to any question will carry some degree of uncertainty, and that uncertainty should be made explicit at every stage in the use of the information. Nevertheless, uncertainty should be interpreted appropriately. When the "fish-X2" relationships were published (Jassby *et al* 1995) and used in supporting salinity standards, debate arose around the fact that these relationships explained only some (often less than half) of the variance in the data. This has been cited time and again as evidence for the importance of "other factors". However, we believe this suite of relationships may be unique among all the world's estuaries in the degree to which estuarine-dependent species respond to flow. The underlying data may be too variable to allow uncertainty to be reduced, and even if other factors are operating, we may never be able to observe them. That is, the finding that flow or X2 accounts for "only" 36% of the variance in early survival of striped bass does not imply that the remaining variance is to be accounted for by factors that can be measured and possibly controlled, such as the concentration of toxic substances or the operation of power plants. It could mean instead that the observations used to develop the indices have only limited precision or that other factors are in operation that are unlikely to be observed.

Uncertainty in the findings of scientists is one of the greatest frustrations of policy-makers who have to rely on scientific input. The best a scientific agency can do is to couch answers in ways that depict the degree of reliability of a certain result. This means that in addition to predicting the outcome of some management action on the ecosystem, the agency should also address the probability and the consequences of other outcomes.

Recognize the Complexity of the Ecosystem

Many of the investigations in the bay/delta system are conducted to determine causes of observed changes in the system and, in most cases, single causes are sought. Such concentration on single factors is an outdated approach (*ie*, reductionism) that ignores the complexity of the ecosystem. Multiple causative factors can operate simultaneously or vary stochastically in relative importance among years, rendering the pursuit of single-factor hypotheses pointless (Bennett *et al* 1995). Furthermore, the system changes continually through new introductions, global warming, and other natural and anthropogenic factors.

Recognize the Limitations Inherent in "Expert Opinion"

In fisheries science in particular, great reliance is placed on the opinions of experts. Such reliance seldom incorporates checks on the accuracy or durability of these opinions, nor does it incorporate peer review. Nevertheless, history is replete with examples in which expert opinion has proved wrong. There is no avoiding the use of expert opinion in situations demanding immediate answers, but there are ways to validate that opinion; for example, by designing and conducting *post-hoc* investigations to test predictions of experts.

Expert opinion is most valuable when used in combination with experimental results to interpret data. An expert with a genuine understanding of the ecosystem may be able to discern which of several potential alternative causes of a pattern is most likely to be operating. However, the opinion of that expert should be guided not only by personal experience but also by the experience of others, learned through collaboration and communication with peers. Thus, the use of expert opinion in formulating policy should rely heavily on the principles identified above.

It is difficult to evaluate the ability of the Interagency Ecological Program to deal with the previous three issues. We see several problems in the way the program responds to these issues, and also several encouraging signs. The main problem is that many scientists in Interagency Program seem to have formed opinions about the workings of the system that do not respond to new information. Counteracting that tendency, though, is the willingness of the Interagency Program to encourage alternative views.

Managing the complex bay/delta system is never going to be easy. As California's population grows and the demand for water increases, opportunities to improve conditions in the ecosystem must rely increasingly on actions not requiring fresh water. The relative effectiveness of these actions should be forecast and determined using the best possible scientific approach and in the context of a good understanding of how the ecosystem works. We hope this editorial will stimulate thoughtful discussion about these issues within the Interagency Program, and that it will lead to refinements in the way the program conducts its science.

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Invasion of the Estuary by Oriental and European Crabs

Kathleen Halat and Kathy Heib

Two recent San Francisco estuary invaders, the Chinese mitten crab (*Eriocheir sinensis)* and the green crab *(Carcinus maenas*) are now abundant and well established in the estuary. Both were introduced within the past 10 years and have a potential to greatly impact the ecosystem. However, their life histories, preferred habitats, and potential impacts are very different.

The Chinese mitten crab is native to rivers and estuaries of China and Korea along the Yellow Sea. These crabs are catadramous, as juveniles grow and develop in fresh water and adult crabs migrate to sea to reproduce. Mitten crabs were first captured in bay shrimp trawls in South Bay during winter 1993, and the number of adult crabs captured by shrimp trawls and several sampling programs has increased each year. Juvenile mitten crabs are distributed throughout most of the tidal sloughs and creeks in the South Bay area, occurring up to 30 miles inland. In tidal areas, burrows are common where there are steep banks high in clay content and lined with vegetation. Densities of juvenile crabs as high as $25/m^2$ occur in some sloughs. Their burrows have accelerated bank erosion rates and slumping in other areas. Over time, the burrowing could pose a serious threat to the structural integrity of delta levees. In addition, in its native range, the mitten crab is secondary host to the oriental lung fluke, a debilitating parasite that can affect humans. Negative spatial interactions between mitten crabs and the introduced red swamp crayfish have been observed in the field; crayfish abundance appears to be negatively correlated with the presence of mitten crabs. Mitten crabs have a wide range of physiological tolerance and can survive out of water for at least a week, increasing likelihood for its transport and establishment. Adults have been captured recently at the SWP and CVP pumping plants.

The green crab is native to the Atlantic coast of Europe and was first collected in South Bay in 1989 or 1990. Its distribution expanded rapidly, and by 1994 green crabs were collected throughout the lower estuary, from South Bay to Carquinez Strait. Green crabs reportedly tolerate a wide range of salinity (5-33 ppt), but we have not collected them at less than 16 ppt. Green crabs primarily inhabit intertidal and shallow subtidal areas; there is some movement to deeper water in winter. Larvae hatch in winter, juveniles settle in spring, and both males and females are mature at 1 year (40 to 50 mm carapace width). The green crab is a voracious predator, consuming primarily bivalves, polychaetes, and small crustaceans. Competition for food may impact shorebirds and other intertidal or shallow subtidal predators, such as the Dungeness crab. The green crab may also compete with juvenile Dungeness crabs for space. Finally, green crabs have consumed small Dungeness crabs in the laboratory, leading to the hypothesis that a large green crab population could decimate a Dungeness crab year class.